An Introduction to X-ray Astronomy

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X-ray Astronomy School 2005

- Preamble
- A brief and idiosyncratic history of X-ray astronomy
- Introductory notes on X-ray data analysis (more this afternoon)

X-ray Astronomy

Emission in the energy range 0.1 - 100 keV (0.12-120 Angstroms). The atmosphere is opaque at these energies so all X-ray astronomy is done using satellites, rockets, and, at the highest energies only, balloons. So :

- Our detectors have to work right the first time - we can't go and fix them. Any problems have to be understood remotely and calibrated.
- There are relatively few X-ray astronomy experiments so public data archives are very important.

In this school we will concentrate on the 0.1-10 keV energy range covered by Chandra and XMM-Newton.

X-ray Processes

X-rays are produced in hot and violent processes. Almost all point-like X-ray sources are variable - some extremely variable. This has two important consequences :

- Monitoring observations are more important in the X-ray band than any other.
- There are few good calibration sources.

The X-ray band includes the K-shell transitions (ie n=2 to 1) of all elements heavier than He. The continuum shape also provides important clues to the emission processes.

X-rays from the Sun

The first astronomical X-ray experiments were performed in 1948 and 1949 using captured WWII V2 rockets. X-rays were detected from the Solar corona by Herb Friedman and collaborators at the US Naval Research Lab (in Washington DC).

It is still not fully understood how the corona is heated to X-ray emitting temperatures.

How to win a Nobel prize

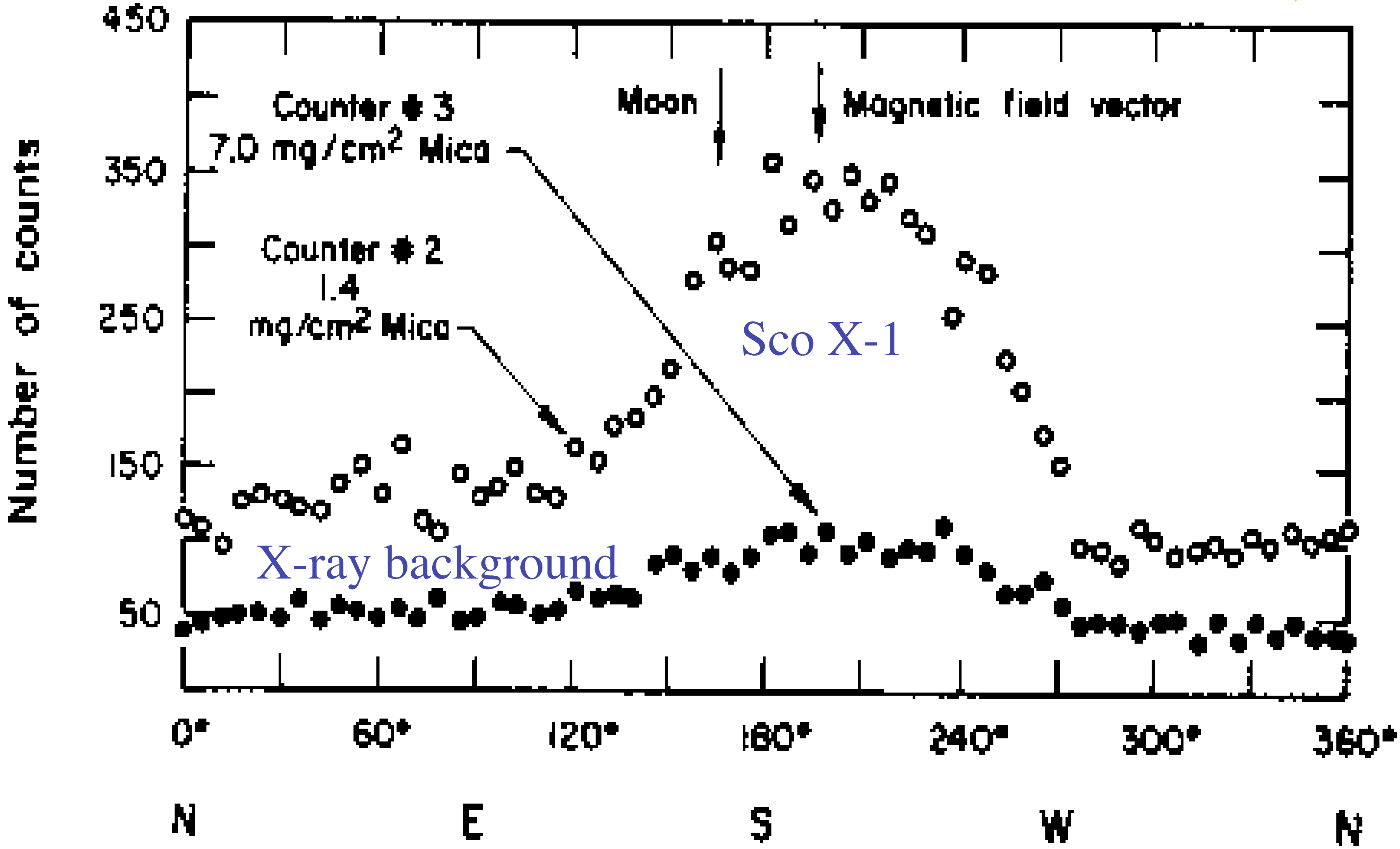
The breakthrough experiment was performed in 1962 by Bruno Rossi, Riccardo Giacconi, and collaborators at American Science and Engineering (AS&E) in Cambridge, MA. After two failures of the Aerobee rocket, they successfully launched a detector to look for X-ray emission from the moon.

As the rocket spun the field-of-view passed over an unexpectedly bright X-ray source. This was designated Scorpius X-1. A follow-up campaign identified the X-ray source as a binary with a compact (neutron star) primary.

Further rocket experiments in the 1960s found other X-ray binaries as well as identifying X-ray emission from several SNR, from M87, Cygnus-A and the Coma cluster of galaxies.

The First Extra-Solar X-ray Detection

Giacconi et al., 1962



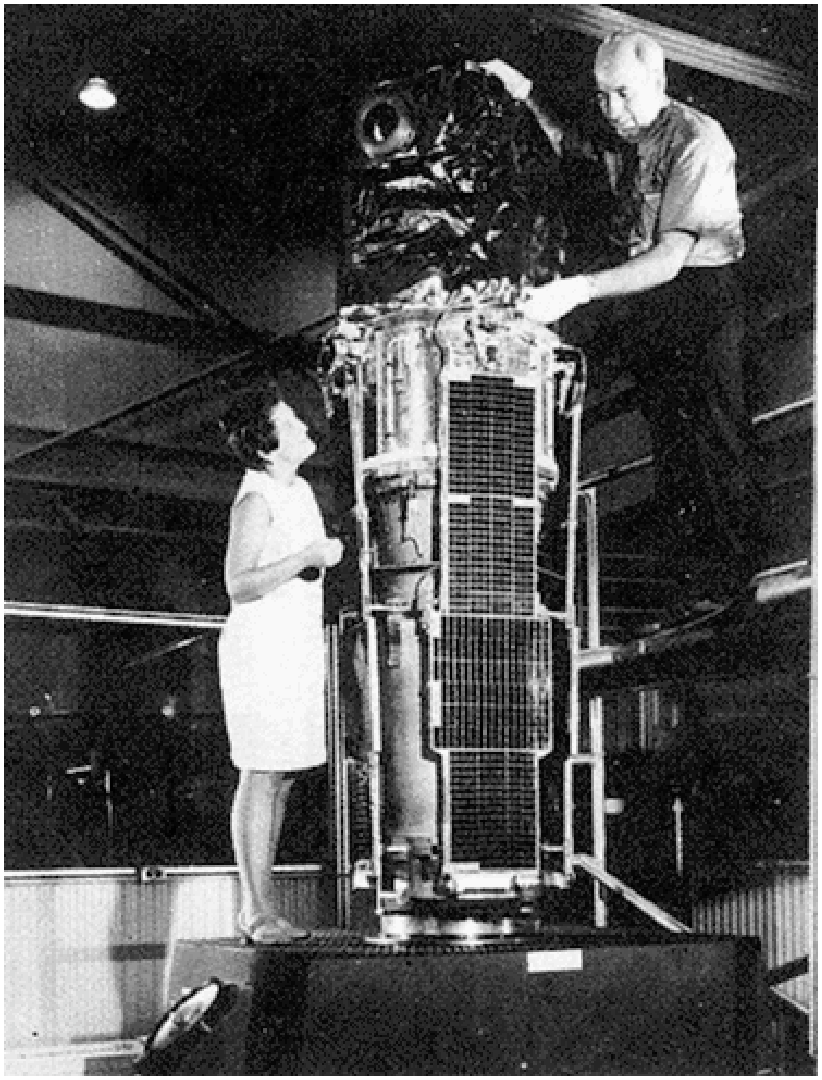
Riccardo Giacconi receives 2002 Physics Nobel Prize from King of Sweden

All-Sky Surveys

The satellite experiments Uhuru (US) and Ariel-V (UK) performed the first all-sky surveys. These used collimated proportional counters with resolutions of degrees so the images of the sky were necessarily crude. However, these surveys detected many galactic binaries, SNR, clusters of galaxies, and active galactic nuclei.

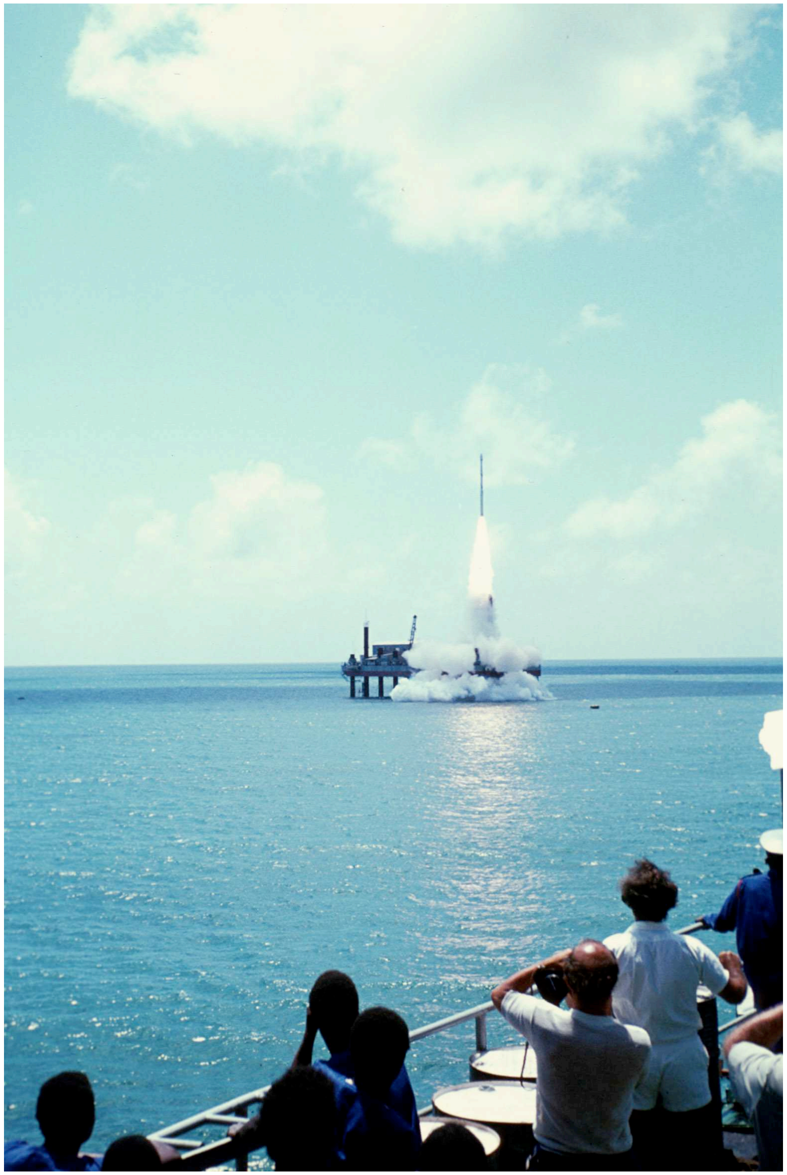
HEAO-1 (US) performed a more sensitive sky survey and made a precise measurement of the intensity and shape of the X-ray background (XRB). There was a long debate about whether the XRB was due to hot gas distributed through the universe or was the sum of many lower flux point sources. The latter is now known to be the case although it is still an interesting question whether the XRB can be completely explained by the sum of individual sources. (Dan Schwartz was PI of the A3 experiment)

Uhuru (“Freedom”)

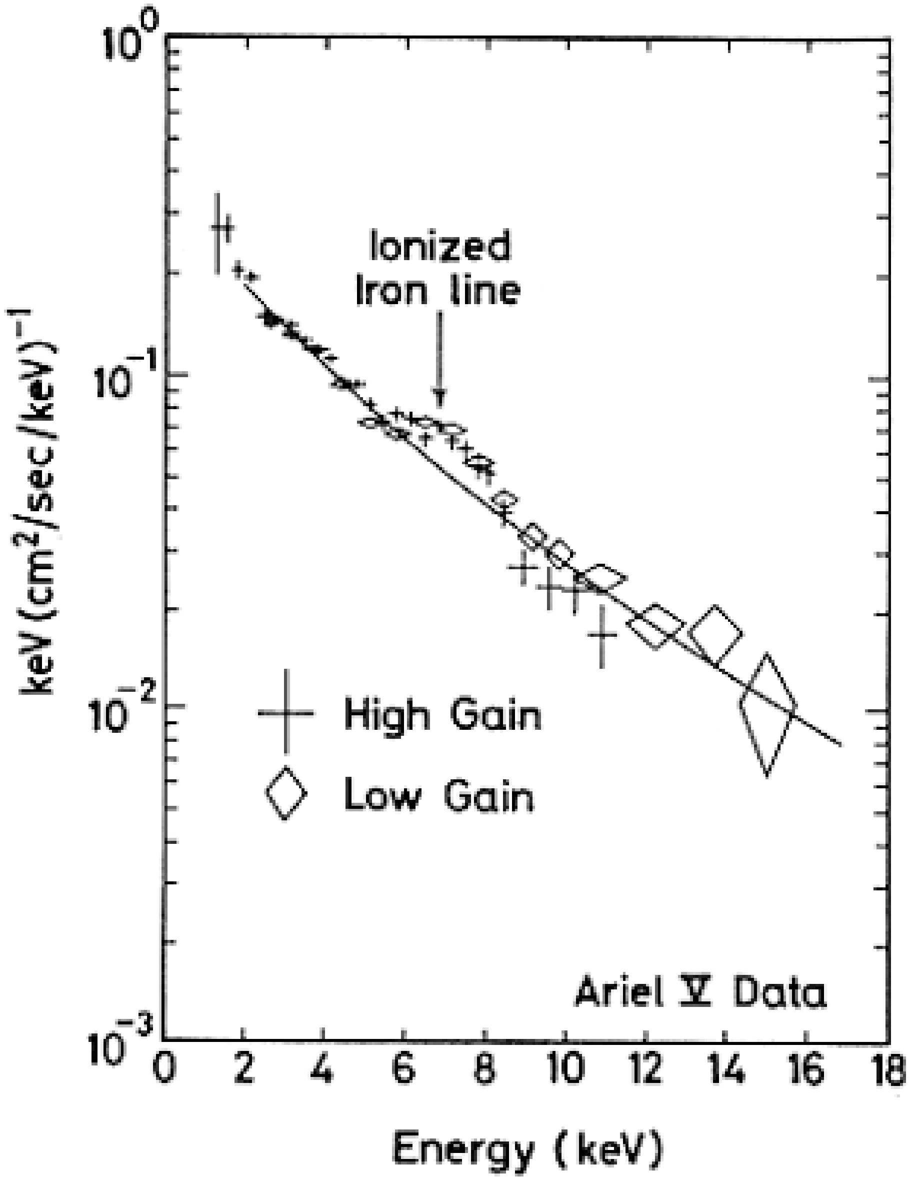


Marjorie Townsend

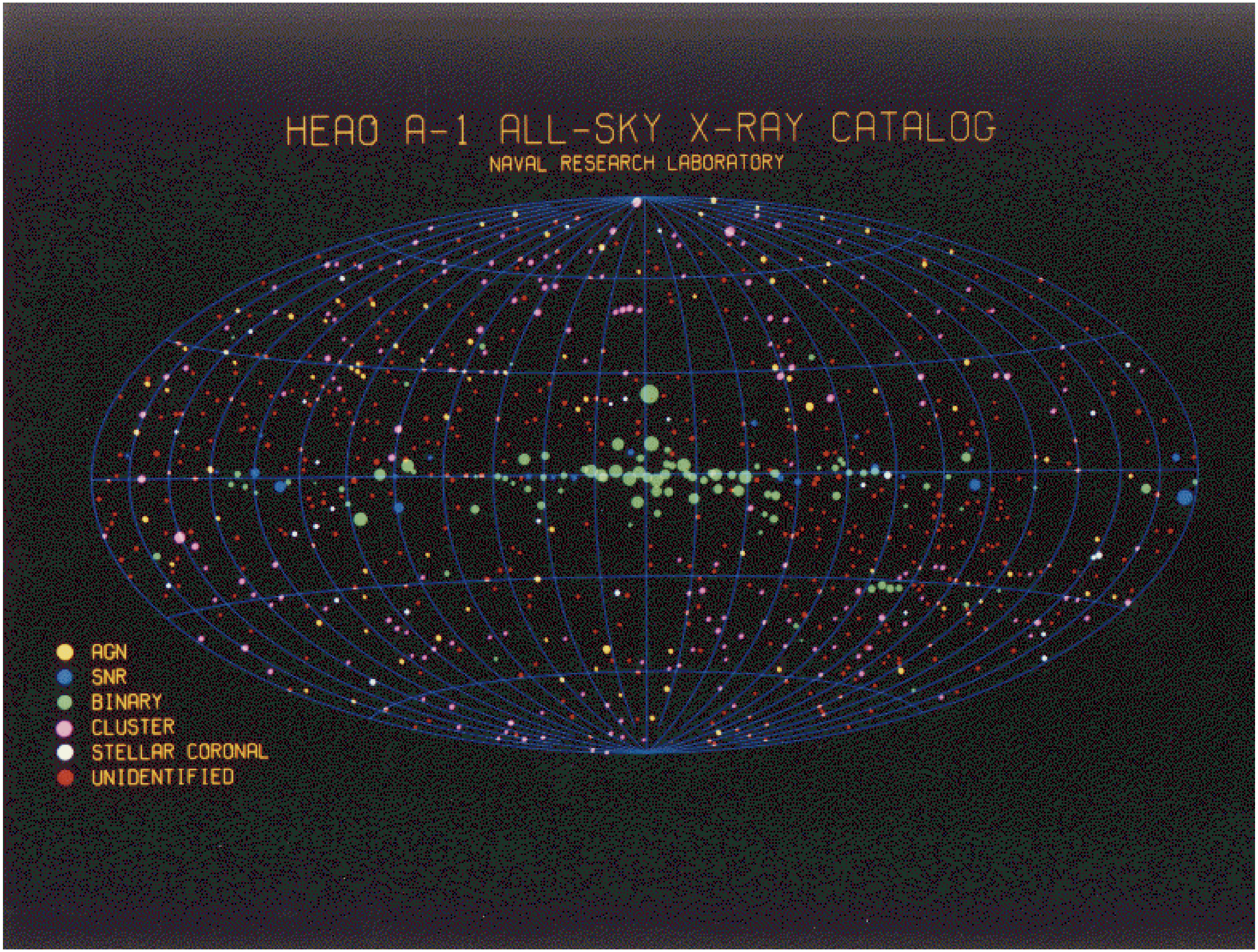
Bruno Rossi



Ariel V launch



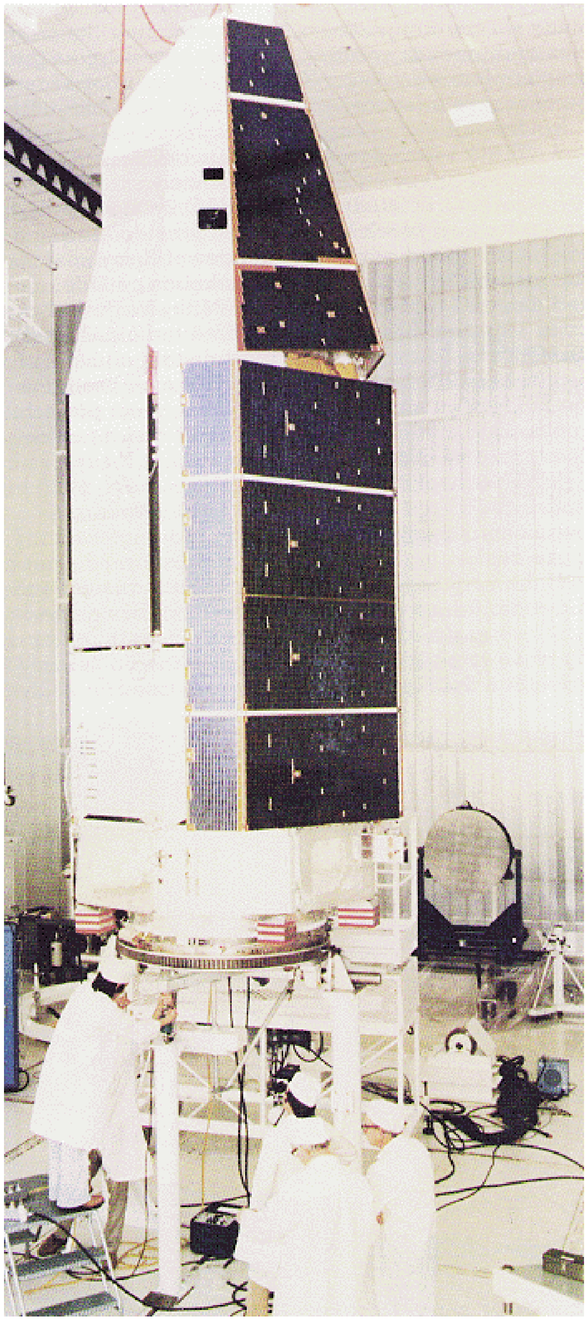
Hot gas in the Perseus Cluster

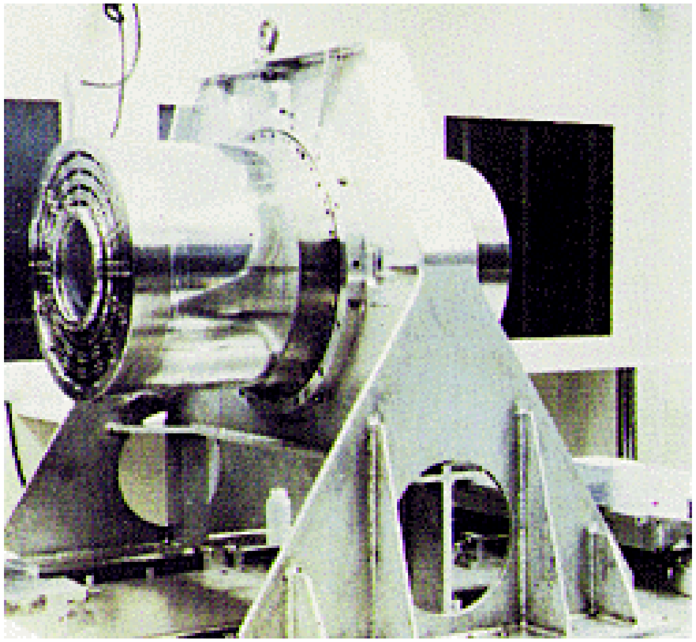

HEAO A-1 ALL-SKY X-RAY CATALOG
NAVAL RESEARCH LABORATORY
AGN
SNR
BINARY
CLUSTER
STELLAR CORONAL
UNIDENTIFIED

X-ray Telescopes

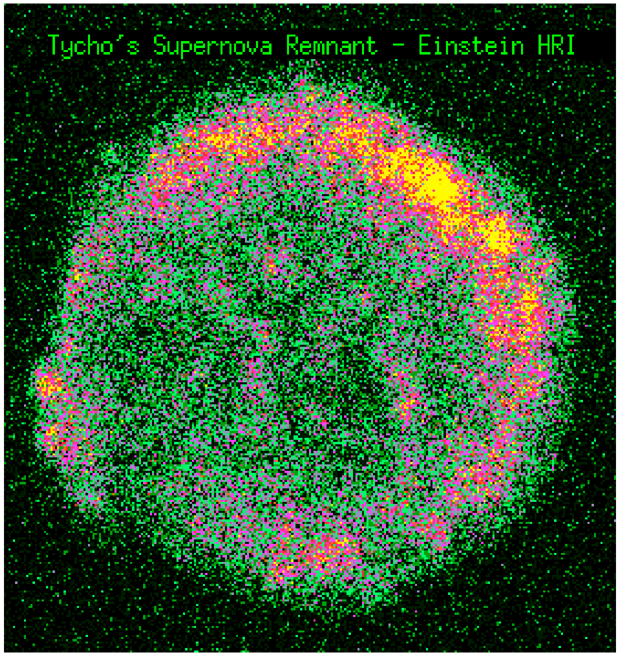
X-ray focussing optics were used first to observe the Solar corona and then transferred to general astronomy with HEAO-2 (US), launched in 1978 and renamed the Einstein Observatory. The telescope imaged X-rays in the energy range 0.5-4.0 keV. Many classes of astronomical objects were detected in X-rays. This was the first X-ray astronomy mission with a guest observer program and a "public archive" (which I used for my PhD thesis).

Its successor, over a decade later, was ROSAT (Germany-US-UK), which performed an all-sky imaging survey in the 0.2-2.5 keV range followed by longer pointed observations at specific targets. This generated a vast public database (which still has lots of potential) - and is a fertile source of targets for Chandra and XMM-Newton.

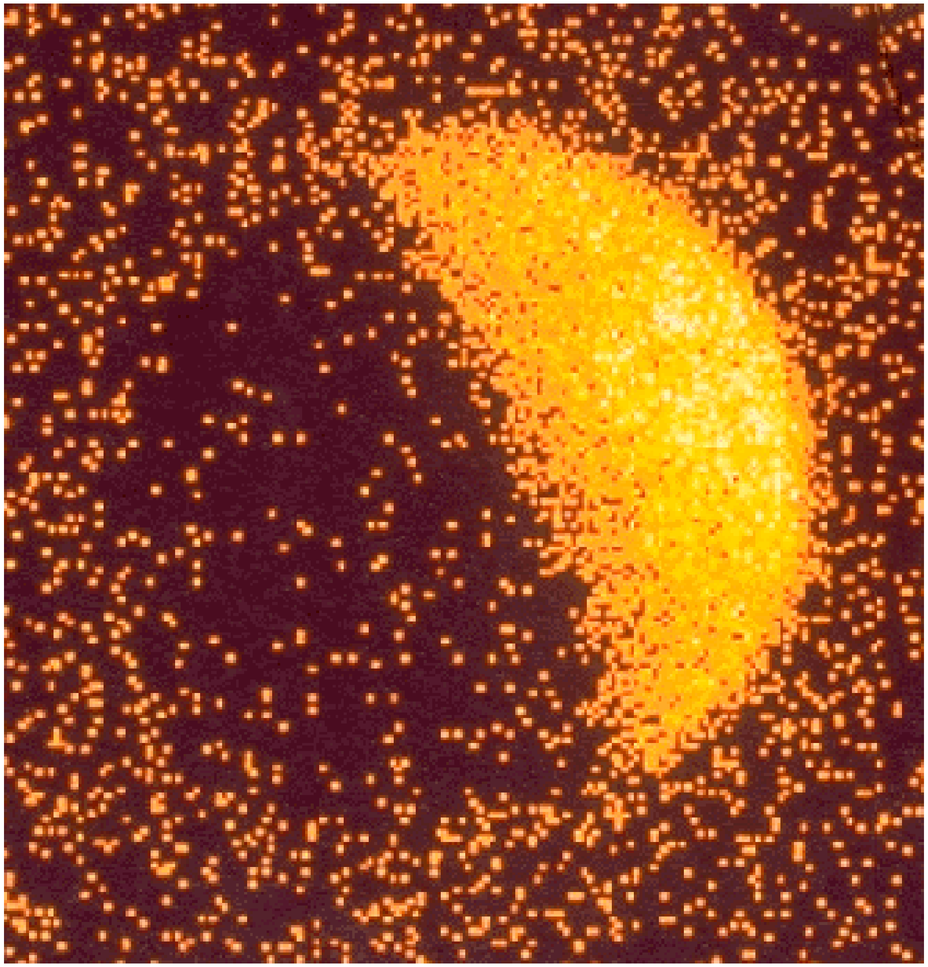




Einstein Observatory



X-ray Detection of the Moon



ROSAT PSPC

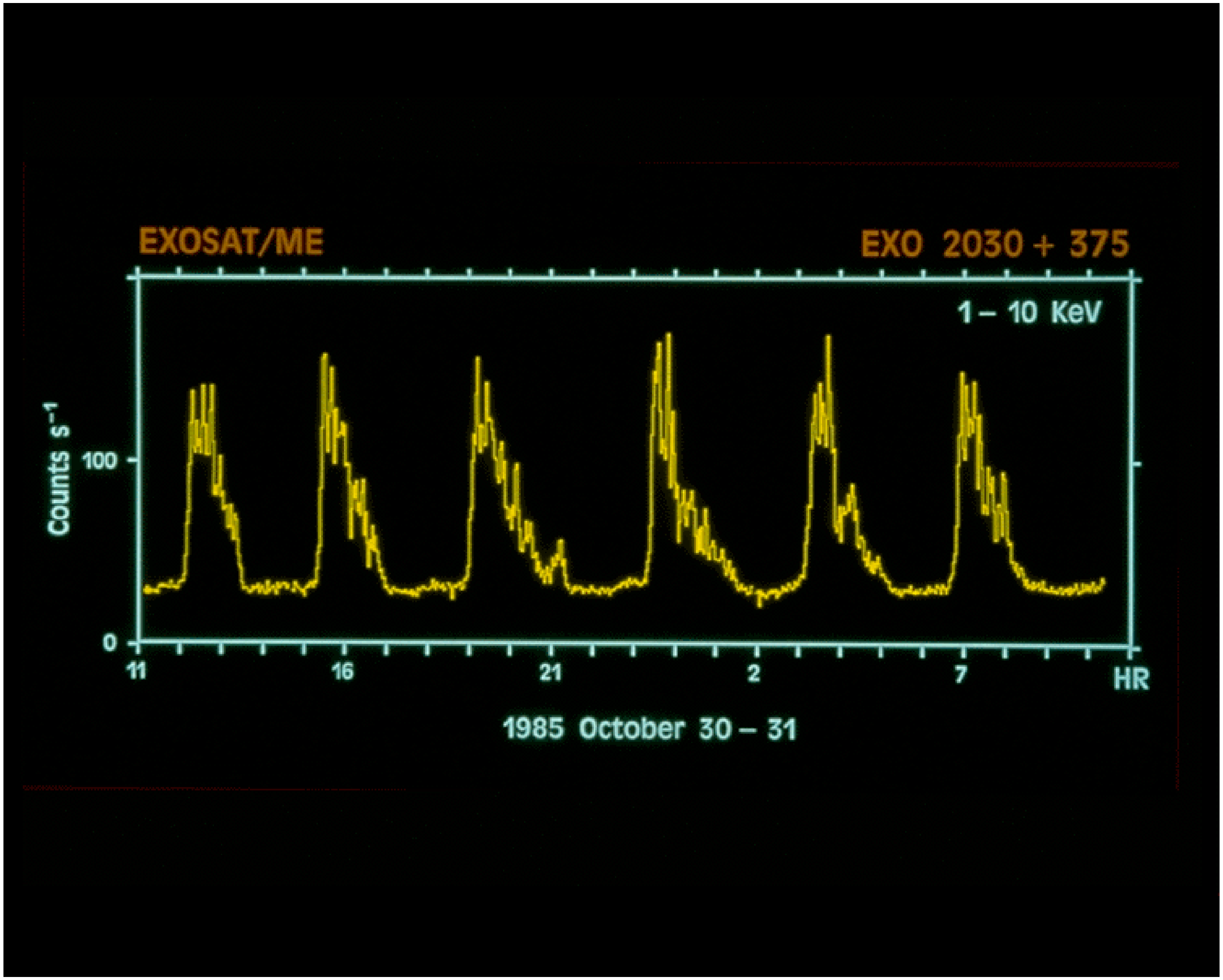
Large proportional counter arrays

Parallel with the development of X-ray telescopes were missions designed to collect large numbers of X-rays from relatively bright sources to perform detailed spectroscopic and timing investigations.

EXOSAT (ESA) was launched in 1983 into a deep orbit which allowed long continuous observations. It discovered Quasi Periodic Oscillations in X-ray binaries.

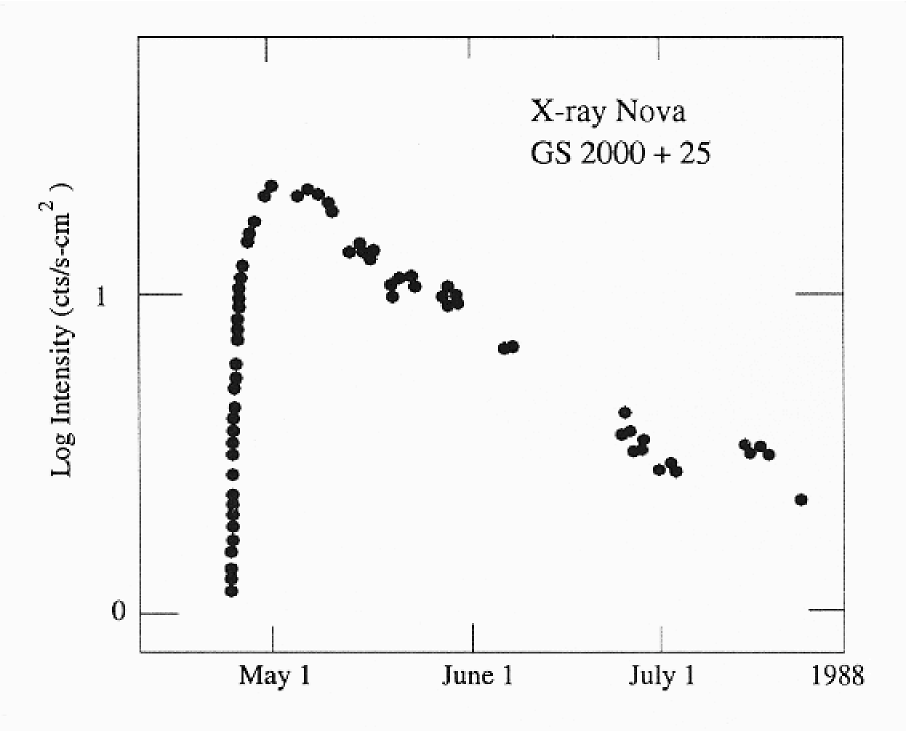
Ginga (Japan-UK) was Japan's third X-ray astronomy satellite and was launched in 1987. Important results were on Black Hole Transients and the detection of Fe lines and Compton reflection in active galactic nuclei.

EXOSAT lightcurve




ASTRO-C LAC-S1

Ginga


X-ray Nova
GS 2000 + 25
Log Intensity (cts/s-cm^2)
1
0
May 1
June 1
July 1
1988

The current culmination of this line is the Rossi X-ray Timing Explorer (RXTE), launched at the end of 1995 and still operating, which has detected kHz oscillations in Galactic binary sources providing possible tests of GR effects in the vicinity of neutron stars and black holes.

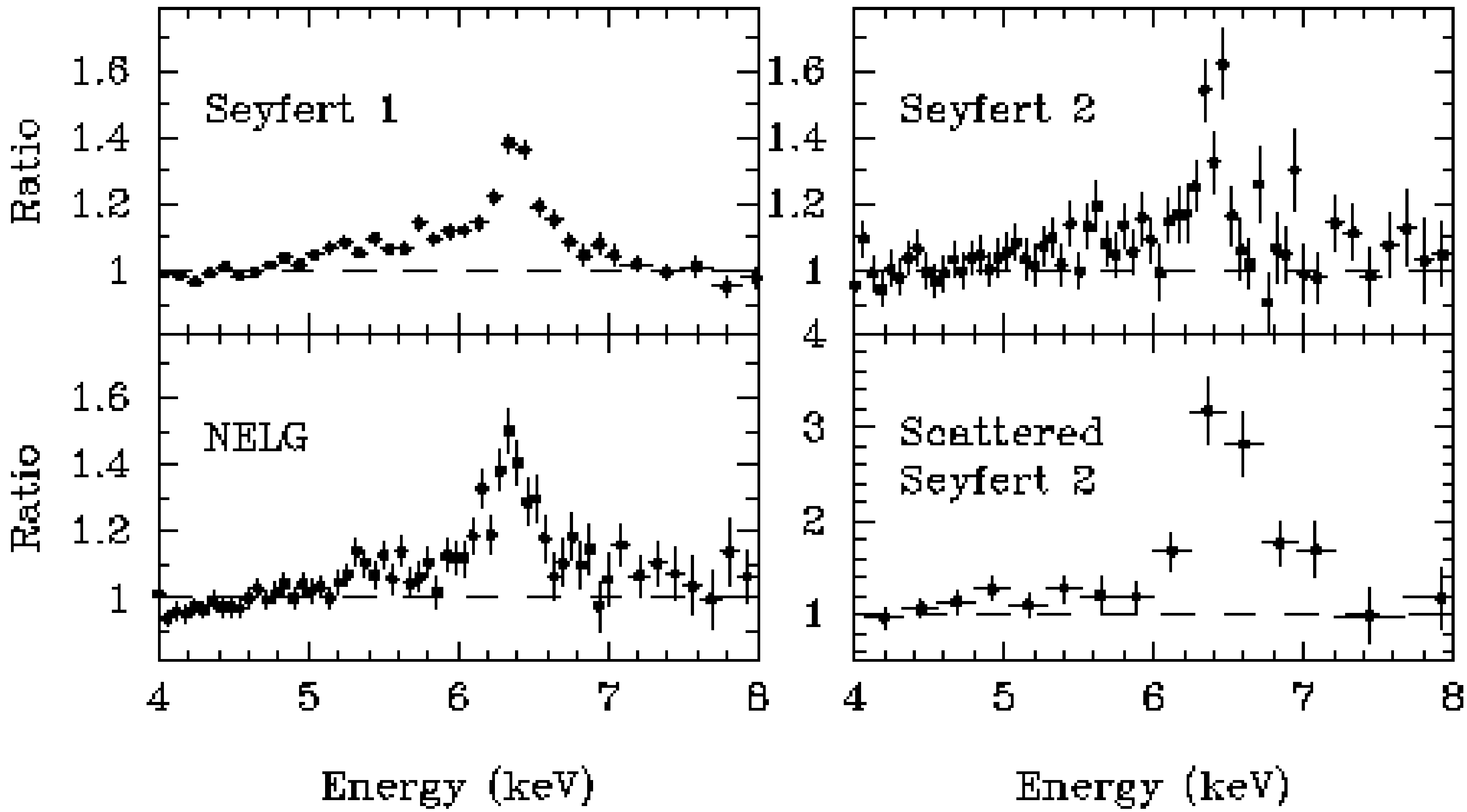
RXTE also carries an all-sky monitor which has produced long-term lightcurves for the brighter sources.

High-throughput telescopes

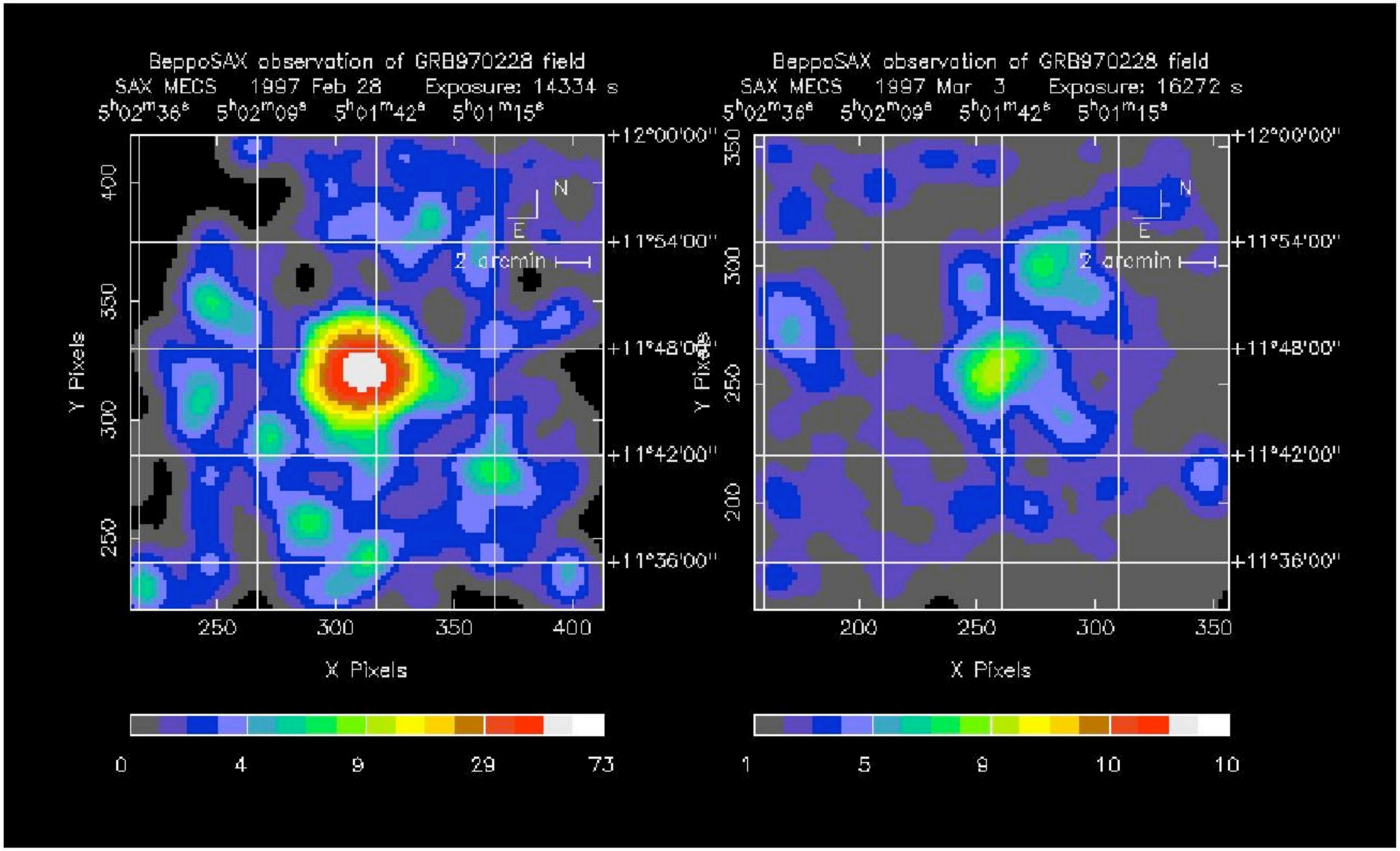
ASCA (Japan-US), launched in 1993, used high-throughput but relatively coarse resolution telescopes that operated in the energy range 0.5-10 keV. The importance of these telescopes was less in the imaging and more in reducing the background - which usually scales with the volume of the detector in space experiments. ASCA detected broad (100,000 km/s) Fe lines from close to the black hole in active galactic nuclei.

BeppoSAX (Italy-Netherlands), launched in 1996, covered a very wide bandpass (0.1-300 keV) using a range of instruments. Its most important result was the discovery of gamma-ray burst afterglows.

ASCA observations of Fe K lines in AGN



Beppo-SAX detection of GRB afterglow

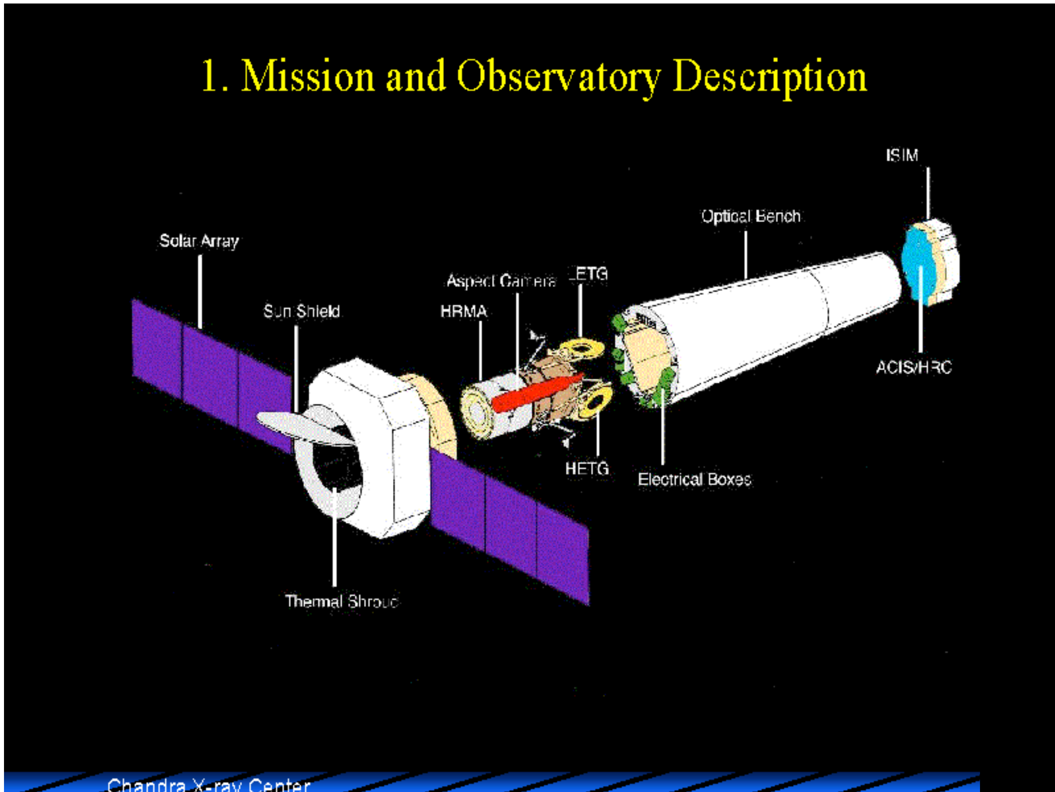


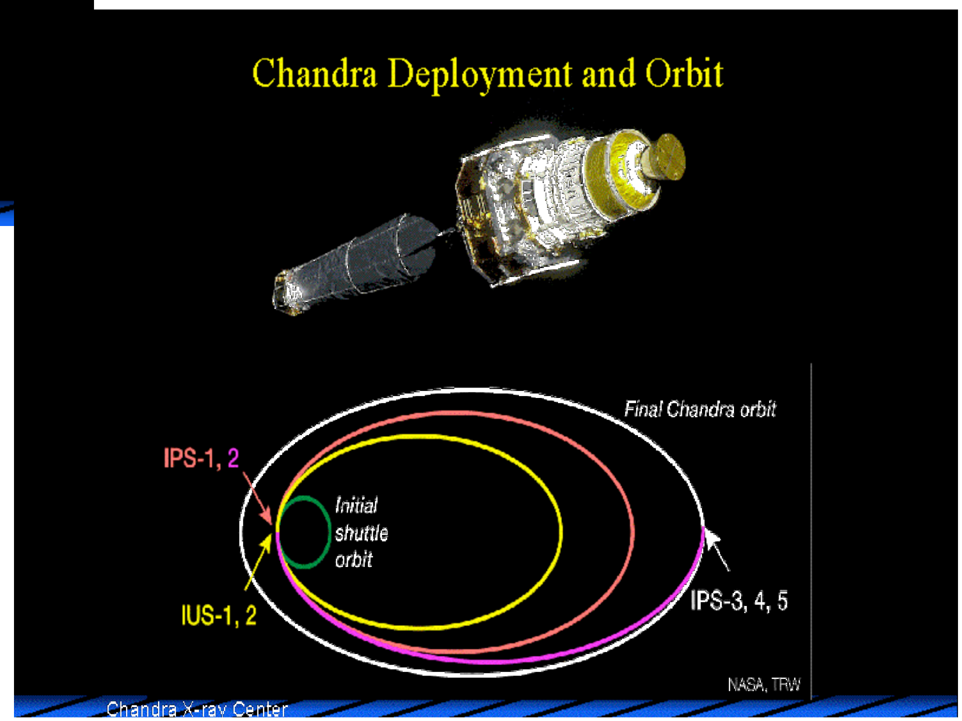
Great Observatories

This brings us up to the present and the two major X-ray astronomy facilities launched in 1999 - Chandra and XMM-Newton.

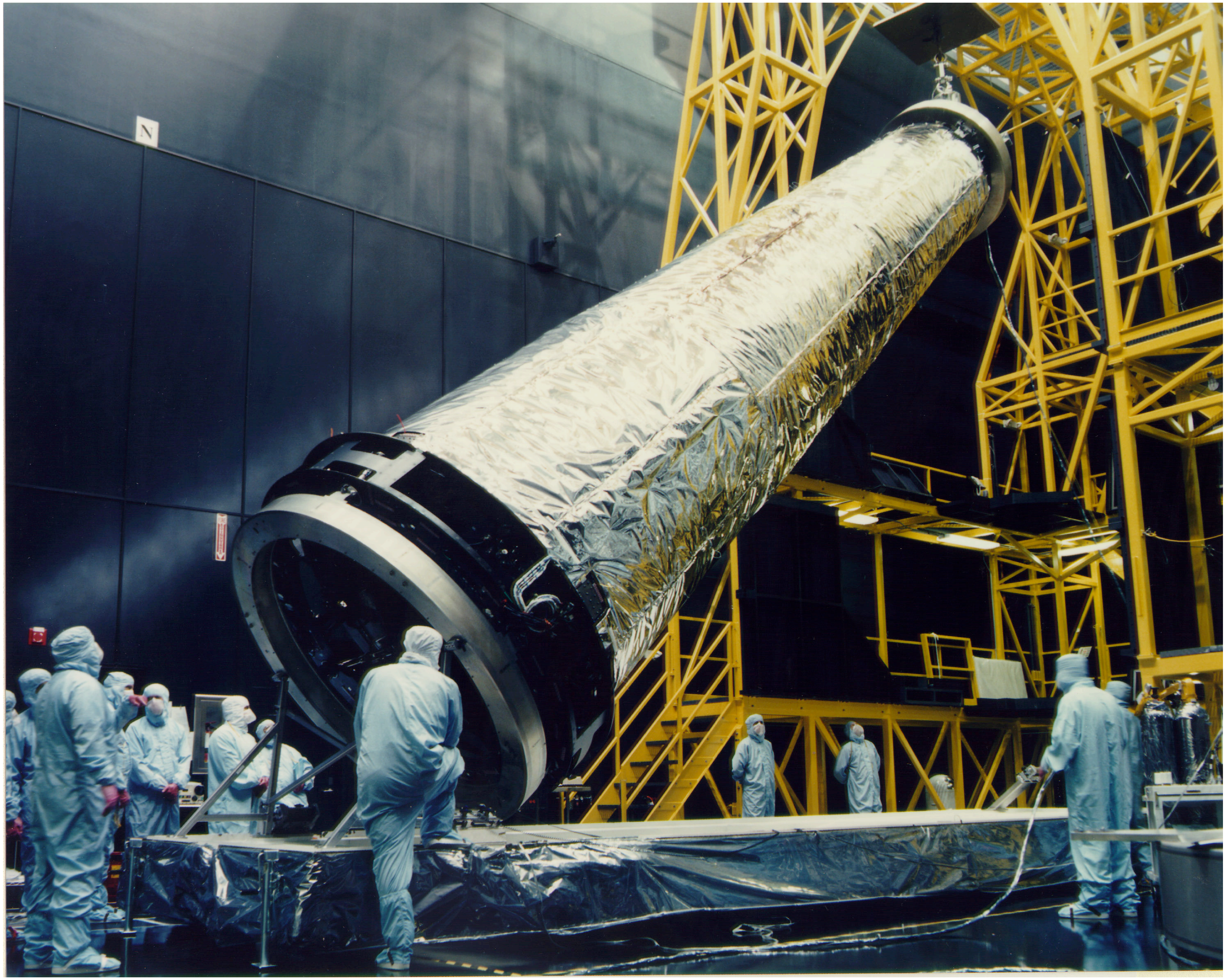
Chandra boasts the best (and most expensive) telescope ever built, giving a sub-arcsecond resolution. Imaging is provided by CCD and microchannel plate imagers. High resolution spectroscopy by two gratings that can be placed in the optical path behind the mirrors.

While Chandra is a successor to ROSAT, XMM-Newton follows the path of ASCA in providing greater mirror area but at lower angular resolution. XMM-Newton has 3 mirrors, 2 of which have reflection gratings, providing simultaneous high resolution spectroscopy and imaging. There is also an optical monitor telescope.


1. Mission and Observatory Description
ISIM
Optical Bench
Solar Array
Aspect Camera
LETG
Sun Shield
HRMA
ACIS/HRC
HETG
Electrical Boxes
Thermal Shroud
Chandra X-ray Center


Chandra Deployment and Orbit
Final Chandra orbit
IPS-1, 2
Initial shuttle orbit
IUS-1, 2
IPS-3, 4, 5
NASA, TRW
Chandra X-ray Center

Chandra



X-ray Astronomy School 2005

$250 million worth of precision optics. The best telescope every built. A resolution of 0.5 arcseconds. Can be used with one of :

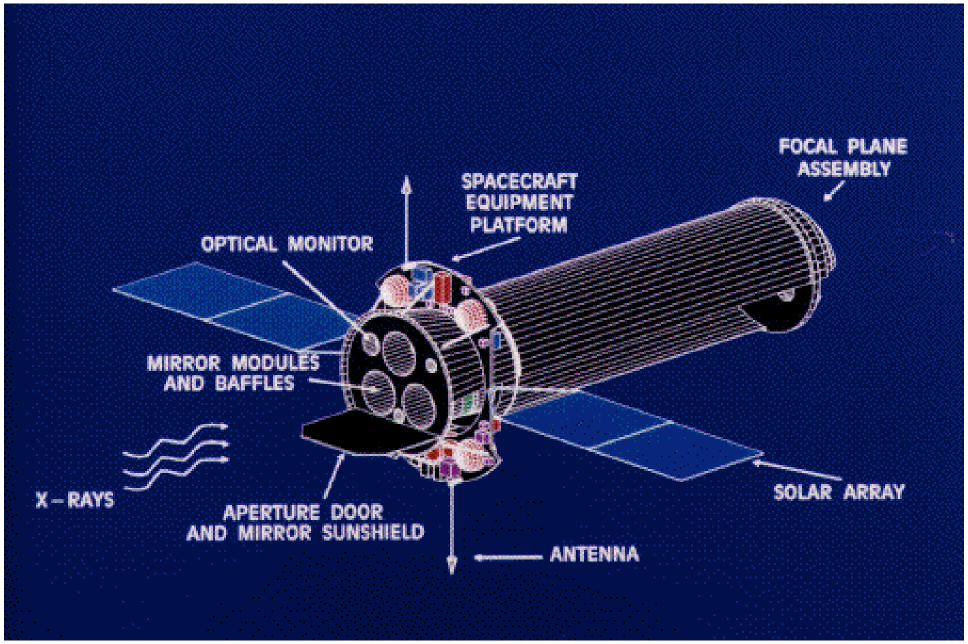
o ACIS - imaging CCD spectrometer with 10 chips. For best spectroscopy of small objects use S3. For best imaging over large fields use I0-I3.

o HRC - imaging channel multiplier. Produces highest spatial resolution images. Also best time resolution (but be careful).

o HETG - pair of gratings dispersing a spectrum onto ACIS. High resolution spectroscopy of small sources for E > 1 keV.

o LETG - grating dispersing spectrum onto HRC or ACIS. High resolution spectroscopy of small sources for E < 1 keV. Used with HRC to get to lowest energies (longest wavelengths) but then there is no order-separation.

XMM-Newton


FOCAL PLANE ASSEMBLY
SPACECRAFT EQUIPMENT PLATFORM
OPTICAL MONITOR
MIRROR MODULES AND BAFFLES
X-RAYS
APERTURE DOOR AND MIRROR SUNSHIELD
ANTENNA
SOLAR ARRAY

Three X-ray telescopes and one optical/UV telescope giving large effective area and simultaneous observations.

- o EPIC - two MOS and one PN CCD spectrometers with 7 and 2 chips respectively. PN has better efficiency at high energies.

- o RGS - two gratings dispersing spectrum onto 8 MOS chips. Each RGS intercepts 50% of the X-rays passing through its telescope.

- o OM - 30cm optical/UV telescope with filter set and two grisms. Generally underused. Limiting sensitivity B=24.

Chandra view of the Galactic center

Wang et al.

Chandra vs. XMM-Newton

Chandra is best for…

- Anything requiring better than 5 arcseconds spatial resolution.
- High resolution spectroscopy for energies < 0.5 or > 2 keV.

XMM-Newton is best for…

- Imaging or imaging-spectroscopy which does not require a resolution of 5 arcseconds or better.
- High resolution spectroscopy for energies 0.5 < E < 2 keV.
- High resolution spectroscopy on extended objects that are larger than 10 arcseconds and smaller than 1 arcminute.

Swift

Gamma-ray burst mission with wide-field hard X-ray detector (BAT), X-ray telescope with CCD detector (XRT), and optical/UV telescope (UVOT).

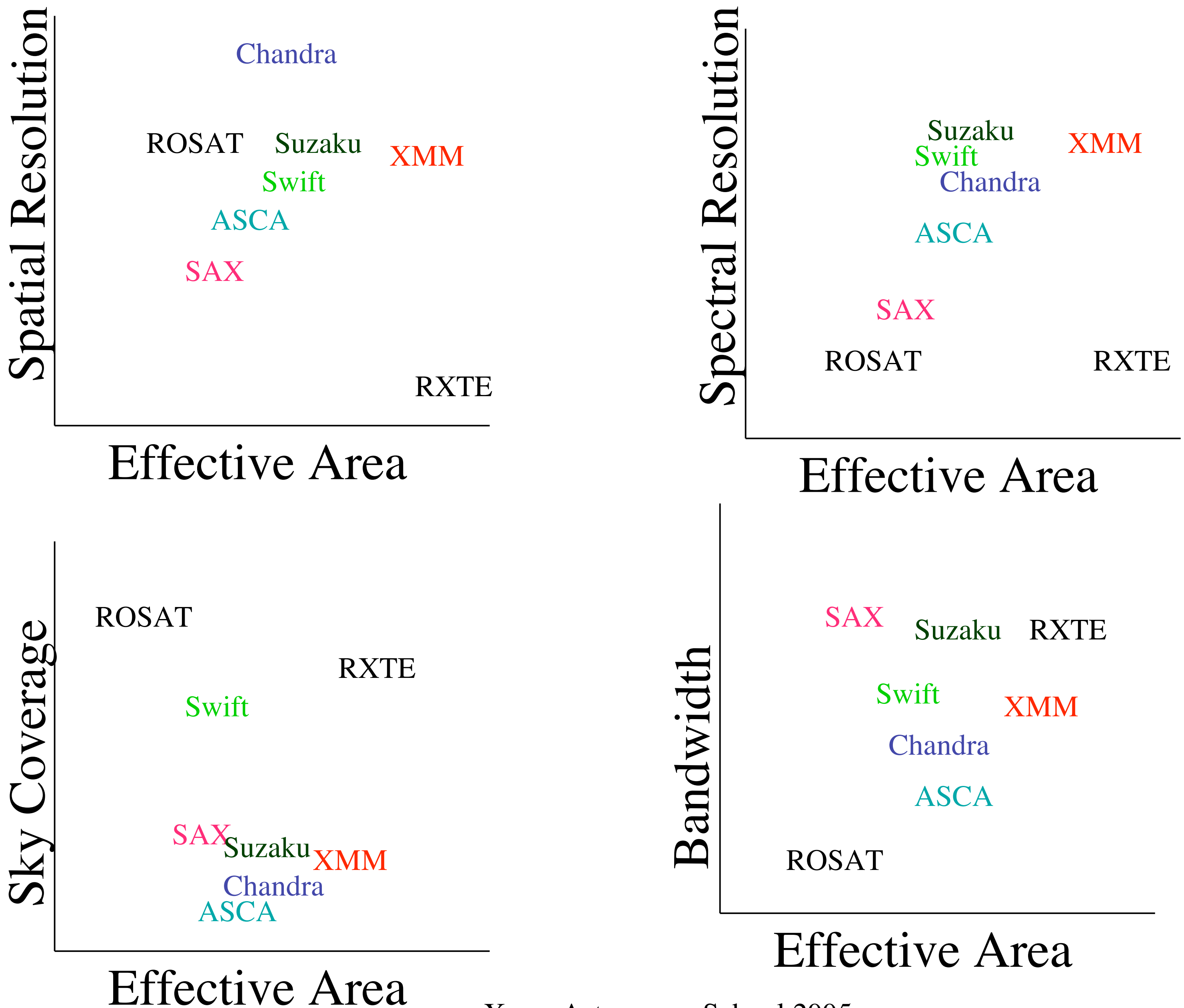
While primarily chasing GRBs, Swift is also observing other sources as time is available. The X-ray telescope has a resolution similar to that of XMM-Newton. The CCD is similar to the EPIC-MOS. The UVOT is a copy of the Optical Monitor on XMM-Newton.

The wide-field detector is producing an all-sky survey in hard X-rays (> 10 keV).

Suzaku

Recently launched Japan-US collaborative satellite. Primary instrument was the XRS - a cryogenic high resolution spectroscopy detector. However it suffered catastrophic loss of He and is no longer operating.

Also includes four X-ray telescopes with CCD detectors (XIS) and a hard X-ray detector (HXD). The XIS has lower background than ACIS or EPIC so will be good for low surface brightness sources. The HXD should be several times more sensitive than previous instruments. The XIS-HXD combination will be good for accretion sources (XRBs and AGN) giving a spectrum from 0.5 - 50 keV.


Spatial Resolution
Chandra
ROSAT
Suzaku
XMM
Swift
ASCA
SAX
RXTE
Effective Area
Spectral Resolution
Suzaku
XMM
Swift
Chandra
ASCA
SAX
ROSAT
RXTE
Effective Area
Sky Coverage
ROSAT
RXTE
Swift
SAX
Suzaku
XMM
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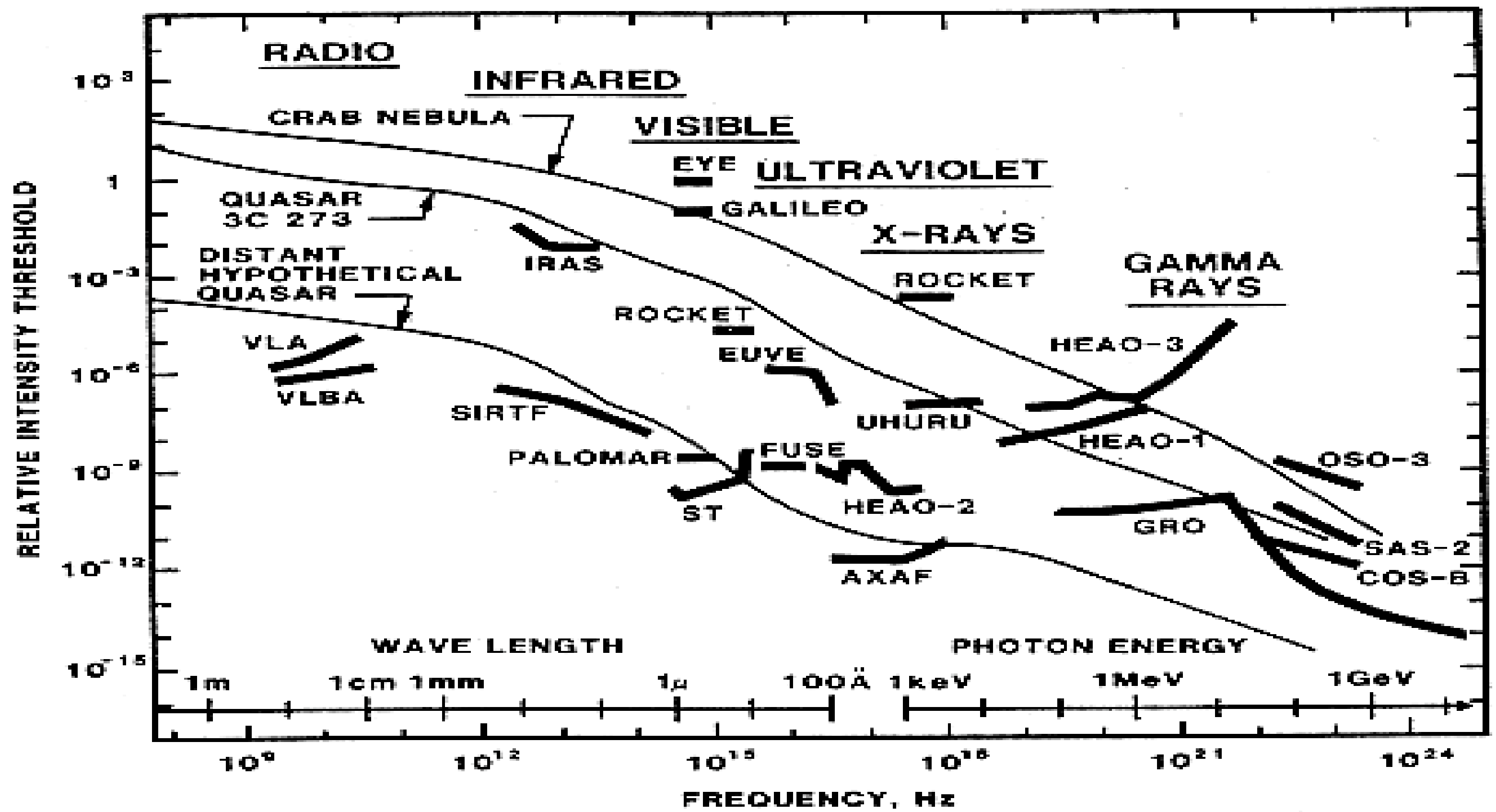
Effective Area
Bandwidth
SAX
Suzaku
RXTE
Swift
XMM
Chandra
ASCA
ROSAT
Effective Area



40 years of X-ray astronomy have provided a billion times improvement in sensitivity and a quarter of a million times improvement in angular resolution.

X-ray data

X-ray detectors are photon-counting in contrast to those in most other wavebands which measure incoming flux. In consequence, basic X-ray data usually comprise lists of events and their attributes.

X-ray datasets are usually photon-limited, particularly for newer missions such as Chandra and XMM-Newton. Images, spectra, and lightcurves created from the event lists may well have a few or even no photons in many bins. The data analysis techniques (and statistics) developed in other wavebands may not transfer to X-ray astronomy.

X-ray data II

The basic data file usually comprises time-tagged events, each with a position (in detector and sky coordinates) and an energy (often called channel, PHA or PI for historical reasons). Thus each event can be thought of as occupying a position in a 4-D space.

The event may have other attributes of interest - eg for CCDs the pattern of pixels from which the charge for this event was accumulated. It is often possible to increase S/N by selecting on these secondary attributes.

After filtering the events as required we project them onto 1-D or 2-D subspaces and bin them up to give images, energy spectra, or lightcurves (time series).

X-ray data III

Each of these binned datasets requires its own calibration products.

- Image analysis uses :
  - exposure maps - the mirror and detector sensitivity across the field-of-view (taking into account any changes in aspect ie pointing direction).
  - point spread function (PSF) - the probability that a photon of given energy and position is registered in a given image pixel.
- Energy spectral analysis uses :
  - response matrices - the probability that a photon of given energy is registered in a given channel.

The 3 Most Important Things for X-ray Data Analysis are :

1. Calibration

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2. **Calibration**

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1. Calibration

2. **Calibration**

3. *Calibration*

(The rest is "just" software, organization, and analysis.)

The Calibration is Never Good Enough

There is always a systematic error term associated with your data analysis. If you have the misfortune to have very high S/N then this systematic term may dominate.

You usually can't add the systematics in quadrature to the statistical uncertainties because the systematic uncertainties are usually correlated.

Don't over interpret data without thinking very hard about the quality of the calibration !

Thank You

Any Questions ?